ORIGINAL PATENT APPLICATION BASED ON:

Docket:	**87434**
Inventors:	**Kevin E. Spaulding**
	Andrew C. Gallagher
	Edward B. Gindele
	Raymond W. Ptucha
Attorney:	**Raymond L. Owens**

EXPRESS MAIL LABEL NO.: **EV293532115US**

Date of Mailing: January 14, 2004

CONSTRUCTING EXTENDED COLOR GAMUT DIGITAL IMAGES FROM LIMITED COLOR GAMUT DIGITAL IMAGES

FIELD OF THE INVENTION

This invention relates to digital image processing and in particular to a method of constructing an extended color gamut digital image from a limited color gamut digital image.

BACKGROUND OF THE INVENTION

Digital images can be represented with a wide variety of color spaces and color encodings. The color gamut of an imaging system is the range of colors that can be represented or produced. An extended color gamut digital image has color values that are outside the limited color gamut of a storage color space. The process of mapping the colors of an extended color gamut digital image to the colors of a storage color space is often referred to as gamut mapping. Regardless of the gamut mapping strategy, there will always be a loss of information and/or a distortion of the color characteristics of the image.

Scene luminance dynamic range can be as large as 1000:1 or more, while most output devices (such as a video display or photographic print) cannot exceed a luminance dynamic range of 150:1 or so. A digital image made up of pixels having color values that represent scene color intensities is an extended color gamut digital image. By mapping the color values of such an image to the limited color gamut of an output device, a great deal of information is lost. For example, the gamut mapping procedure of mapping colors of an extended dynamic range digital image to the video "sRGB" color space generally discards a great deal of information, often due to the large difference in the luminance dynamic ranges. The process of using gamut mapping to map the colors of an extended color gamut digital image to the color gamut of a storage color space representing an output device (for example sRGB color space) is called rendering.

Rendered digital images (also called limited color gamut digital images) are generally very convenient for direct display on an output device. For example, limited color gamut digital images encoded in the sRGB color space look good on a video monitor. However, the information loss associated with the

rendering process that was used to produce the limited color gamut digital image makes it difficult to manipulate the image.

Rendered digital images can suffer from traditional photographic problems. These problems can be caused by things such as exposure error, colored illuminant, contrast variability, and the like. These problems are very difficult to fix with direct manipulation of the rendered digital image data. For example, the application of a linear function to the pixel values of a rendered image in the sRGB color space appears to modify the exposure, color saturation, and contrast of the image. Thus, it is difficult to correct or enhance a limited color gamut digital image.

However, the information in the extended color gamut digital image is useful for readily modifying the digital image. For example, when the colors of the extended color gamut digital image are related to the logarithm of the scene exposure, then exposure adjustments can be made simply by adding a constant to each color component value in the image. Contrast problems can often be corrected by applying a linear or nonlinear function to the image data.

Therefore, one method of applying modifications to a limited color gamut digital image includes the steps of:

a) producing a reconstructed extended color gamut digital image from the limited color gamut digital image;

b) enhancing the reconstructed extended color gamut digital image with an image modification step; and

c) producing an enhanced limited color gamut digital image by rendering the modified reconstructed extended color gamut digital image.

Steps b) and c) are both commonly known in the art of image processing. A successful method of producing a reconstructed extended color gamut digital image from a limited color gamut digital image must overcome several obstacles. First, the rendering process used to produce a limited color gamut digital image from an extended color gamut digital image involves a loss of information, as previously described. Second, it is common to represent the limited color gamut digital image with only 8 bits per color channel of each pixel.

This quantization, coupled with the gamut mapping, makes it very difficult to accurately produce a reconstructed extended color gamut digital image. The process of producing a reconstructed extended dynamic range digital image from a limited color gamut digital image is referred to as "derendering".

Spaulding et al. in U.S. Patent 6,285,784 describe a method of applying manipulations to a limited color gamut digital image. In the described method, a limited color gamut digital image is combined with a residual image to form a reconstructed extended color gamut digital image. This reconstructed extended color gamut digital image is enhanced with modifications such as color balance adjustment or tone scale adjustment. U.S. Patent 6,285,784 describes an effective method for applying a modification to a limited color gamut digital image by making an extended color gamut digital image. Unfortunately, U.S. Patent 6,285,784 does not describe improving a limited color gamut digital image not having an associated residual image.

In U.S. Patent 6,335,983, McCarthy et al. describe a derendering process by applying an inverse color adjustment function to a source digital image. This method can be used to generate an extended color gamut digital image from a limited color gamut digital image for the purpose of enhancing the image. The de-rendered image, the extended color gamut digital image, can then be improved with image modifications. However, their resulting image (the reconstructed extended color gamut digital image) can occasionally contain objectionable artifacts such as color contouring and quantization artifacts.

SUMMARY OF THE INVENTION

It is therefore an object of the present invention to provide an improved method of producing a reconstructed extended color gamut digital image from a limited color gamut digital image.

Still further, it is an object of the present invention to provide an improved method of derendering a limited color gamut digital image.

It is another object of the present invention to provide a method for forming reconstructed extended color gamut digital images from a variety of different limited color gamut color spaces.

These objects are achieved by a method for reconstructing an extended color gamut digital image from a limited color gamut digital image represented in a particular limited color gamut color space which was derived from an initial extended color gamut image, comprising:

a) transforming the limited color gamut digital image in the particular limited color gamut color space to a reference color space forming a limited color gamut digital image in a reference color space;

b) providing a modified inverse color adjustment function which, when such function operates on the limited color gamut digital image in the reference color space, produces the reconstructed extended color gamut digital image having reduced highlight color saturation for highlight color values when compared with corresponding color values of the initial extended color gamut image; and

c) operating on the limited color gamut digital image in the reference color space with the modified inverse color adjustment function to form the reconstructed extended color gamut digital image having reduced levels of color contouring and quantization artifacts.

ADVANTAGES

The present invention uses a modified inverse color adjustment function, which operates on a limited color gamut digital image to construct an extended color gamut digital image. This constructed extended color gamut digital image has reduced color saturation for highlight color values, which facilitates reduction in color contouring and quantization artifacts.

The invention has the additional advantage that reconstructed extended color gamut digital images can be determined from input images in a variety of different limited color gamut color spaces.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a functional block diagram showing the component parts of the present invention;

FIG. 2 is a block diagram showing a prior art method of generating a limited color gamut digital image from an extended color gamut digital image;

FIG. 3 is a block diagram of one embodiment of the color adjustment function shown in FIG. 1;

FIG. 4 is a preferred inverse encoding function $H^{-1}(x)$;

FIG. 5 is a preferred tone scale function $R(x)$;

FIG. 6 is a preferred encoding function $G(x)$;

FIG. 7 is a block diagram of one embodiment of the inverse color adjustment function shown in FIG. 1;

FIGS. 8A and 8B are plots of the two functions that make up the inverse encoding function $G^{-1}(x)$;

FIG. 9 is an inverse tone scale function $R^{-1}(x)$;

FIG. 10 is a preferred encoding function $H(x)$;

FIG. 11 is a block diagram of one embodiment of the modified inverse color adjustment function shown in FIG. 1;

FIG. 12 shows an inverse tone scale function $R^{-1}(x)$ and two modified inverse tone scale functions $R_m^{-1}(x)$;

FIG. 13 is a plot of the function $f(sat)$;

FIG. 14 is a functional block diagram showing a method for implementing the present invention for digital images in a variety of different input color spaces; and

FIG. 15 is a functional block diagram showing an alternate method for implementing the present invention for digital images in a variety of different input color spaces.

DETAILED DESCRIPTION OF THE INVENTION

In the following description, a preferred embodiment of the present invention will be described as a software program. Those skilled in the art will readily recognize that the equivalent of such software can also be constructed in hardware. Because image processing algorithms and systems are well known, the present description will be directed in particular to algorithms and systems forming part of, or cooperating more directly with, the method in accordance with the present invention. Other aspects of such algorithms and systems, and hardware and/or software for producing and otherwise processing the image

signals involved therewith, not specifically shown or described herein, can be selected from such systems, algorithms, components, and elements known in the art. Given the description as set forth in the following specification, all software implementation thereof as a computer program is conventional and within the ordinary skill in such arts.

Still further, as used herein, the computer program can be stored in a computer readable storage medium, which can comprise, for example, magnetic storage media such as a magnetic disk (such as a floppy disk) or magnetic tape; optical storage media such as an optical disc, optical tape, or machine readable bar code; solid state electronic storage devices such as random access memory (RAM), or read only memory (ROM); or any other physical device or medium employed to store a computer program.

A digital image is comprised of one or more pixels. Each pixel has an associated color value. The color value of a pixel can be indicated by one or more color component values. Typically, the color component values indicate intensities of red, green, and blue (although other numbers of color components values are possible). Taken together, the color component values describe the color value of the pixel. Each digital image channel is comprised of a two-dimensional array of pixels. For monochrome applications, a single color component value describes the color value of each pixel. Motion imaging applications can be thought of as a time sequence of digital images. Those skilled in the art will recognize that the present invention can be applied to, but is not limited to, a digital image channel for any of the above mentioned applications.

A preferred embodiment of the present invention is shown in FIG. 1. A first or initial extended color gamut digital image **10** is input, along with a color adjustment function **22** to an adjust color values step **21**. Step **21** will be described in more detail hereinbelow. The output of step **21** is a limited color gamut digital image **32**.

A reconstructed extended color gamut digital image **66** is produced from a limited color gamut digital image **32** using information describing the color adjustment function **33**. Note that the information **33** preferably describes the

color adjustment function **22** that was used by the adjust color values step **21** to generate the limited color gamut digital image **32**. However, the present invention still achieves the desired result when the information **33** does not exactly correlate to the color adjustment function **22**. This is important because the exact color adjustment function **22** is not always known by a system employing the described invention, but an approximate color adjustment function is often known. An inverse color adjustment function **34** is produced from the information **33**. A modify inverse color adjustment function step **62** is used to adjust the inverse color adjustment function **34** to reduce the severity and frequency of artifacts (as judged by a human visual inspection) resulting from quantization and gamut compression in the reconstructed extended color gamut digital image **66**. A reconstruct extended color gamut digital image step **65** is used with inputs of a limited color gamut digital image **32** and the modified inverse color adjustment function **63** to produce the reconstructed extended color gamut digital image **66**.

Note that a digital camera can capture the first or initial extended color gamut digital image **10**, and perform the adjust color values step **21** according to the color adjustment function **22** within the camera hardware. Many digital cameras output an sRGB color space digital image, which is a limited color gamut digital image. In addition, the first or initial extended color gamut digital image **10** can be derived by scaling a photographic film, such as a print film or a transparency film. Note that the film itself can be an extended color gamut image.

To fully appreciate the present invention shown in FIG. 1, a prior art method for generating a limited color gamut digital image **24** is shown in FIG. 2 (see U.S. Patent 6,335,983). An extended color gamut digital image **20** has color values that are outside the limited color gamut of a storage color space. An adjust color values step **21** is used to limit the color values to those that will fit within the limited color gamut of the storage color space using a color adjustment function **22**. Next, a represent image in storage color space step **23** is used to form a limited color gamut digital image **24**.

The color gamut of an imaging system is the range of colors that can be represented or produced. An out-of-gamut color is a color that cannot be

produced or represented in that imaging system. The color gamut of the storage color space will often be smaller than, or at least different from, the original color gamut of the extended color gamut digital image **20**. As a result, there generally will be colors in the extended color gamut digital image **20** that cannot be represented in the storage color space, for example, in the case where the extended color gamut digital image **20** is a scan of a photographic negative having a luminance dynamic range of 1000:1. A typical storage color space such as a video RGB color space (e.g., sRGB color space) has a luminance dynamic range of less than 150:1.

Therefore, color values for the out-of-gamut colors (color values of the extended color gamut digital image **20** that are not in the gamut of the storage color space) must somehow be modified in order to store the color values in the storage color space. In prior art methods, contouring and quantization artifacts can occur when attempting to recover the original extended color gamut color values. A contouring artifact refers to the visual impression that an imaging system has discrete "steps" between different color values. For example, an object in the image that should appear as a gradual contour from one color value to a different color value instead appears as a series of steps between the color values. A quantization artifact refers to the visual impression that color values intermediate to other color values are missing from a digital image. Contouring and quantization artifacts are often closely related, and can occur within the same spatial region of a digital image. These artifacts generally reduce the quality of an image. In the present invention, these artifacts are reduced in magnitude and frequency. Essentially, this is accomplished by the present invention by reducing the color saturation of those color values (generally highlight color values) that would likely produce artifacts. Highlight color values relate to the lighter color values in a digital image. Preferably, in reference to an 8-bit sRGB digital image (a limited color gamut digital image), the highlight color values are those color values having an average color component value of 240 or above. Alternatively, the highlight color values are those color values having an average color component value of 0.8 or above when the color values relate to linear exposure.

The adjust color values step **21** is used to adjust the color values of the extended color gamut digital image to fit within the limited color gamut of the storage color space, forming adjusted color values. In this step, out-of-gamut colors in the extended color gamut digital image are modified to be within the limited color gamut. It is preferable to use a color adjustment function that is substantially invertible. For example, a gamut compression strategy such as described in U.S. Patents 5,539,540 and 5,583,666 could be used.

The extended color gamut can have a larger luminance dynamic range than can be represented in the limited color gamut. In this case, one aspect of the implementation of the adjust color values step **21** is typically the application of a tone scale function. The tone scale function might be applied to the luminance channel of the image, or alternatively to each color channel of a color digital image representation. Specific examples of color adjustment functions can be found in U.S. Patents 5,539,540, 5,583,666, and 6,335,983.

The color adjustment function **22** can be implemented in many different ways. In some cases, it might be applied as a set of simple mathematical transformations, such as scale factors, etc. In other cases, it might be implemented with a polynomial function or set of one-dimensional look-up-tables or matrix operations, or a multi-dimensional look-up-table (such as described in U.S. Patent 4,500,919), or a combination thereof.

Once the adjusted color values have been determined, the next step is to represent the adjusted color values in the storage color space indicated by step **23**. The output of step **23** is a limited color gamut digital image **24**.

As shown in FIG. 1, the present invention produces a reconstructed extended color gamut digital image **66**. There are two goals that guide the creation of the reconstructed extended color gamut digital image **66**. The first goal is that the color values of pixels of the reconstructed extended color gamut digital image **66** should be as close as possible to the first or initial extended color gamut digital image **10**. The second goal is that the reconstructed extended color gamut digital image **66** should be as free from color contouring and quantization artifacts as possible. These goals conflict sometimes. For example, a reduction in artifacts

can only be achievable by increasing the average color value differences between the first or initial extended color gamut digital image **10** and the reconstructed color gamut digital image **66**. The reduction in artifacts is generally achieved by limiting the gradients within the inverse color adjustment function **34** with the step **62**, resulting in the modified inverse color adjustment function **63**. In the preferred embodiment, the limitation of the gradient in the modified inverse color adjustment function **63** results in reduced color saturation for highlight color values in the reconstructed extended color gamut digital image **66** relative to the saturation of color values of corresponding pixels in the first extended color gamut digital image **10**. However, the color saturation for non-highlight color values in the reconstructed extended color gamut digital image **66** is similar (+ or –10%) to the color saturation of color values of corresponding pixels in the first or initial extended color gamut digital image **10**.

Knowledge of the color adjustment function **22** is used to produce a reconstructed extended color gamut digital image **66** from a limited color gamut digital image **32**. As shown in FIG. 1, information describing the color adjustment function **33** is used to generate an inverse color adjustment function **34**.

There are many different types of information that can be used to describe the color adjustment function **22**. For example, a multi-dimensional look-up-table can be used to describe the color adjustment function **22**. In this case, the nodes of the multi-dimensional look-up-table would store the adjusted limited color gamut color values for a lattice of original extended color gamut color values. Conversely, the multi-dimensional look-up-table can be used to store the inverse transformation. In this case, the nodes of the multi-dimensional look-up table would store the original extended color gamut color values for a lattice of limited color gamut color values.

In some cases, the information **33** is a set of parameters. For example, the parameters might include a set of matrix coefficients. In addition, the coefficients of a polynomial can also be included among the parameters.

For some applications, there can be a limited number of standard color adjustment functions **22** that can be used. In this case, rather than storing the

actual color adjustment function **22**, it might be preferable to store an identifier to indicate which color adjustment function from a set of standard color adjustment functions **22** were used. In the case where the limited color gamut digital image **24** is an sRGB digital image produced by a digital camera, the information **33** can be determined from a database that contains the color adjustment function information **33** for each make and model of digital camera, or from some other identifier associated with the limited color gamut digital image **24**. Further, a human operator could supply the information **33**.

If the limited color gamut digital image **32** has no associated information **33**, then the information **33** can be supplied as a system default. For example, if a limited color gamut digital image **32** from an unknown digital camera is input to the step **65**, then the information **33** describing a known color adjustment function **22** is used as a default. For instance, the information describing the color adjustment function **33** could describe the color adjustment function of U.S. Patent 5,583,666 as a default.

It is important to realize that, while it is preferable that the information **33** relates directly to the color adjustment function **22**, the present invention can successfully generate a useful reconstructed extended color gamut digital image **66** even when the information **33** only approximately corresponds to the color adjustment function **22**.

The limited color gamut digital image **32** is preferably a digital image encoded in the sRGB color space (defined at http://www.w3.org/Graphics/Color/sRGB.html). Widely available consumer digital cameras, such as the Kodak DX3900 Digital Camera, typically produce limited color gamut digital images in the sRGB color space. In addition, the limited color gamut digital image **32** could originate from a scan of a film, or a scan of a print.

The first or initial extended color gamut digital image **10** and the reconstructed extended color gamut digital image **66** can take many forms. Preferably, the color values of the reconstructed extended color gamut digital image **66** represent colors values from the original scene. Preferably, the pixel

values of the reconstructed extended color gamut digital image **66** are also related to the logarithm of the scene exposure. The reconstructed extended color gamut digital image **66** is capable of having color values that are outside of the limited color gamut of a storage color space. Preferably, the extended color gamut digital image is encoded with 12 bits per pixel per color component value.

The reconstruct step **65** is used to expand the color values of the limited color gamut digital image to fit within the extended color gamut, producing a reconstructed extended color gamut digital image **66**. The expansion is governed by the modified inverse color adjustment function **63**. Each color value of the image **66** is ideally as close as possible to the corresponding color value of the first or initial extended color gamut digital image **10** of FIG. 1, with the added constraint that contouring and quantization artifacts are minimized.

The previously described information **33** is used to determine an inverse color adjustment function **34**. Mathematical techniques exist for inverting functions and are known by those skilled in the art. The functional inverse function $f^{-1}(x)$ of a function $f(x)$ is the function that minimizes a squared error between an initial domain value (x) and the result of applying the inverse function to the function, as given in the following equation:

$$\min_{f^{-1}(x)} \int_x \left[x - f^{-1}(f(x))\right]^2 .$$

Many mathematics texts present methods for inverting functions and matrices, both of which can be included within the color adjustment function **22**. While the inverse color adjustment **34** preferably minimizes the squared error between the extended color gamut digital image **10** and the reconstructed extended color gamut digital image **66**, the inverse color adjustment function **34** also contains very high gradients that can produce contouring and/or quantization artifacts in the reconstructed extended color gamut digital image **66**.

A modify inverse color adjustment function step **62** is used to modify the inverse color adjustment function **34** in such a manner as to reduce the magnitude and frequency of visibly objectionable artifacts (such as contouring and/or quantization artifacts) in the reconstructed extended color gamut digital

image **66**. The output of the step **62** is a modified inverse color adjustment function **63** that is input to step **65** for producing a reconstructed extended color gamut digital image **66** from a limited color gamut digital image **32**.

Color, in digital images, is often represented as a multi-dimensional vector of color component values. It is common for color to be represented as a three-dimensional vector, such as an sRGB color value. Thus, the color adjustment function **22** and the inverse color adjustment function **34** are generally multi-dimensional transformations. Step **62** can be thought of as a way to modify the multi-dimensional transformation inverse color adjustment function **34**. Step **62** generally reduces or places a limitation on the local gradient of the inverse color adjustment function **34** in order to reduce the frequency and magnitude of artifacts in the reconstructed extended color gamut digital image **66**.

If the inverse color adjustment function **34** includes a series of component functions (such as look-up-tables and matrices), then step **62** can modify any or all of the component functions to produce the modified inverse color adjustment function **63**.

As an example, FIG. 3 shows a color adjustment function **22** including a series of component functions that determines a limited color gamut color values from extended color gamut color values. This color adjustment function **22** is used to produce a limited color gamut digital image **24** as shown in FIG. 2 where the storage color space (i.e. the limited color gamut) is the sRGB color space. The color adjustment function **22** is applied to each color value of an extended color gamut color value **48**, producing corresponding color values of the limited color gamut color value **50**. The color adjustment function **22** includes each of the component functions in the specific order as shown. First, an inverse encoding function $H^{-1}(x)$ **41** is applied to the data to convert from the extended color gamut color values that are related to the log of scene exposure and encoded with 12 bits per color component value per pixel to color values that are linearly related to scene exposure. FIG. 4 illustrates the preferred inverse encoding function $H^{-1}(x)$. Referring back to FIG. 3, the next component function is a color

primary matrix function E **42** that produces new color values by computing linear combinations of the original color values. The matrix E is preferably

$$E=\begin{bmatrix} 2.05 & -0.79 & -0.26 \\ -0.21 & 1.25 & -0.04 \\ -0.02 & -0.14 & 1.16 \end{bmatrix}.$$

Next, the tone scale function $R(x)$ **44** as previously described reduces the luminance dynamic range of the extended color gamut to more closely match that of the limited color gamut. FIG. 5 illustrates the preferred tone scale function, showing the preferred mapping from color values having the extended dynamic range of the extended color gamut to color values having a limited dynamic range of the limited color gamut. Finally, the encoding function $G(x)$ **46** of FIG. 3 is used to properly distribute the color values for display on a video monitor. FIG. 6 illustrates the preferred encoding function $G(x)$. Those skilled in the art will recognize that a multi-dimensional transformation exists that could be used as the color adjustment function **22** and produce equivalent limited color gamut digital image as with the FIG. 3 color adjustment function including several component functions.

The color adjustment function **22**, including the inverse encoding function $H^{-1}(x)$ **41**, the color primary matrix function E **42**, the tone scale function $R(x)$ **44**, and the encoding function $G(x)$ **46** has a corresponding inverse color adjustment function **34**, shown in FIG. 7. The inverse color adjustment function **34** is applied to each color value of an limited color gamut color value **50**, producing corresponding extended color gamut color values **48**. This inverse color adjustment function **34** is produced by inverting the order of the component functions and inverting each of the component functions, as would be known to those skilled in the art of image processing. FIG. 7 shows that the component functions of the inverse color adjustment function include the inverse encoding function $G^{-1}(x)$ **56**, the inverse tone scale function $R^{-1}(x)$ **54**, the inverse color primary matrix function E^{-1} **52**, and the encoding function $H(x)$ **51**. The inverse of the encoding function $G^{-1}(x)$ **56** is broken up into two functions in the preferred embodiment. The first function, shown in FIG. 8A, is a linear function designed to

increase the bit-depth of the limited color gamut digital image, which is typically encoded with 8 bits per color component per pixel. The bit-depth function shown in FIG. 8A increases that bit-depth from 8 to 12 bits per color component per pixel. A second function, plotted in FIG. 8B, shows the relationship between the output of the first function shown in FIG. 8A and linear rendered exposure values. These two function shown in FIGS. 8A and B, taken together, form the inverse encoding function $G^{-1}(x)$. If desired, the two functions can readily be cascaded to form a single function that represents the inverse encoding function $G^{-1}(x)$.

A plot of the inverse tone scale function $R^{-1}(x)$ referred to in FIG. 7 is shown in FIG. 9. Taking the inverse of a matrix is well known by those skilled in the art $E^{-1}=\begin{bmatrix} 0.52 & 0.35 & 0.13 \\ 0.09 & 0.86 & 0.05 \\ 0.02 & 0.11 & 0.87 \end{bmatrix}$.

A plot of the encoding function $H(x)$ referred to in FIG. 7 is shown in FIG. 10. The inverse color adjustment function **34** of FIG. 7, if applied to each color value of a limited color gamut digital image, would produce corresponding color values of a reconstructed extended color gamut digital image. Determining the color values of a reconstructed extended color gamut digital image with the aforementioned inverse color adjustment function **34** can produce color contouring and quantization artifacts. For that reason, in FIG. 1 the inverse color adjustment function **34** is modified with a modify inverse color adjustment function step **62** to produce a modified inverse color adjustment function **63**. This modified inverse color adjustment function **63**, if used to produce color values of a reconstructed extended color gamut digital image, is less likely to produce artifacts than the inverse color adjustment function **34**. The nature and method of the modifications performed in the modify inverse color adjustment function step **62** is described below.

The preferable modified inverse color adjustment function **63** produced by the modify inverse color adjustment function step **62** is shown in FIG. 11. The modified inverse color adjustment function **63** is applied to each color value of an limited color gamut color value **50**, producing corresponding

extended color gamut color values **48** in such a manner that color contouring and quantization artifacts are minimized. The modified inverse color adjustment function **63** includes a series of component functions, several of which are exact matches to those of the inverse color adjustment function **34** shown in FIG. 7. The first component function is the inverse encoding function $G^{-1}(x)$ **56**, already shown in FIGS. 8A and B. Intermediate pixel values output from the inverse encoding function $G^{-1}(x)$ range from 0 to 1.0 for each color component value, corresponding to a linear intensity of light. Those skilled in the art will recognize that the choice of the data range is arbitrary, and the present invention can readily be adapted to operate on color component values that have a different encoding, as would be apparent to those skilled in the art.

The next component function is the decontouring matrix function *D* **72**. The purpose of the decontouring matrix is to reduce the saturation of the color values that might appear as color contouring or quantization artifacts. The application of matrix *D* serves to prevent contouring and quantization artifacts, as higher saturation color values have a higher probability of appearing as quantization or contouring artifacts in the subsequent component functions of the modified inverse color adjustment function **63**. Preferably, the decontouring matrix is a 3x3 matrix having the following form:

$$D = \begin{bmatrix} d & r(1-d) & (1-r)(1-d) \\ 0.5(1-d) & d & 0.5(1-d) \\ (1-r)(1-d) & r(1-d) & d \end{bmatrix}$$

where d ranges from 0.4 to 1.0 and is preferably 0.7. Parameter r ranges from 0 to 1.0 and is preferably 5/6. The decontouring matrix *D* is preferably applied to a color value described by a red, green, and blue, component coefficient, with the following equation:

$$c_{new} = D * c$$

where c_{new} represents the color component values resulting from the application of the decontouring matrix function *D* **72** to the original color component values.

c preferably is a column vector of the red, green, and blue color component values.

$$c = \begin{bmatrix} r \\ g \\ b \end{bmatrix}$$

where r, g, and b represent the red, green, and blue color component values.

It is well known how to apply a 3x3 matrix to modify a color value by those skilled in the art of image processing. For color values having no saturation component (i.e. neutral color values where all color component values are equal) the matrix D has no effect.

Preferably, the decontouring matrix D **72** is applied to only those color values that are likely to produce color contouring or other artifacts. This is accomplished by making the value d of the decontouring matrix D **72** dependent on the color value of each pixel, thereby selecting a specific decontouring matrix D for each pixel's color value. The value d is a function of the average a of the color component values that represent the color value. The average a ranges from 0 (for a black color value) to 1.0 (for a white color value). The specific value of d used to produce the decontouring matrix D **72** for the color value of a specific pixel is d_{new}, calculated with the following equations:

$$d_{new} = 1 \qquad \text{when } a <= T_1$$

$$d_{new} = (1-d)*(a-T_1)/(T_1-T_2) + d \qquad \text{when } T_1 < a < T_2$$

$$d_{new} = d \qquad \text{when } a >= T_2$$

where T_1 and T_2 are thresholds that are preferably set to 0.42 and 0.78, respectively.

The next component function is the modified inverse tone scale function $R_m^{-1}(x)$ **74**. The modified inverse tone scale function $R_m^{-1}(x)$ **74** is a modified version of the inverse tone scale function $R^{-1}(x)$ **54**. The modification includes a limitation on the derivative (slope) of the inverse tone scale function **54**. FIG. 12 shows a plot of the inverse tone scale function **54** (solid line **81**), and two versions of the modified inverse tone scale function **74**, produced with two

different slope limits. The dashed line **82** represents a modified inverse tone scale function produced with a slope limit of 8, and the dotted line **83** represents a modified inverse tone scale function produced with a slope limit of 5. The preferred slope limit is 8. Applying a slope limit to a function is well known in the art of image processing as, for example, is described by Goodwin in U.S. Patent 5,134,573. The purpose of the modification of the inverse tone scale function is to limit the gain of the inverse tone scale function, thereby reducing the frequency and magnitude of contouring or quantization artifacts. Limiting the slope of the modified inverse tone scale function reduces the artifacts by decreasing the color saturation in the highlights of the reconstructed extended color gamut digital image **66** relative to that of the first or initial extended color gamut digital image **10**. By de-saturating the color values with the decontouring matrix function **72** prior to the modified inverse tone scale function **74**, the contouring and quantization artifact occurrence are further reduced. Those skilled in the art will recognize that other modifications can be applied to the inverse tone scale function $R^{-1}(x)$ **54** to produce the modified inverse tone scale function $R^{-1}(x)$ **74**.

Referring back to FIG. 11, the next component function is the inverse of the decontouring matrix D^{-1} **76**. Inverting a 3x3 matrix is well known in the art and will not be further described. The purpose of the inverse of the decontouring matrix is to restore the color saturation of color values. For color values passing through a linear or nearly linear portion of the inverse tone scale function, the decontouring matrix and its inverse has no or very little effect. For color values passing through nonlinear portions of the inverse tone scale function, the decontouring matrix de-saturates the color value (i.e. reduces the range of the different color components of the color value). As a result, a narrower portion of the inverse tone scale function (having a lower average slope) affects the color value. The lower slope therefore is less likely to produce color contouring or quantization artifacts when applied to the color value.

The next component function is an inverse color primary matrix E^{-1} **52**. The purpose of the inverse color primary matrix is to change the primaries of the color representation. This component function is identical to the similar

function in the inverse color adjustment function previously described with reference to FIG. 7.

Referring again to FIG. 11, the next component function is the extended color gamut encoding function *H(x)* **51** that essentially spaces the code values of the extended color gamut digital image **66** such that they are proportional to the log of scene exposure. A plot of the preferred *H(x)* is shown in FIG. 10.

The final component function is a desaturation function **78**. The desaturation function **78** has the purpose of reducing the color saturation of those pixels that can contain color contouring or quantization artifacts. Contouring is more objectionable when it also involves changes in color. For example, a noticeable contour step from white to gray is less objectionable than a contour step from white to yellow-gray. The desaturation function **78** partially de-saturates those pixels that are likely to exhibit color contouring. The operation of the desaturation function **78** is as follows. A desaturation coefficient s is determined for the color value of each pixel of the image. The application of the desaturation coefficient s to the color value is performed as follows. A saturation component is determined for the color value. The saturation component is multiplied by the saturation coefficient s. Those skilled in the art will recognize that the saturation of a color value can be modified by a scale factor (the desaturation coefficient) in a number of different ways. Preferably, a neutral component is determined for the color value according to the following equation:

$$neu = \sum_{i=1}^{P} a_i c_i$$

where P is the number of color component values that represent the color value, a_i is the weighting coefficient for the i^{th} color component. Preferably,

$$\sum_{i=1}^{P} a_i = 1$$

c_i is the value of the i^{th} color component.

In the preferred case where a color value's color components are *red*, *green*, and *blue* components, the preferable equation for forming the neutral component is

$$neu = 0.4\ red + 0.5\ green + 0.1\ blue$$

where *red, green*, and *blue* represent the color component values of the color value.

Next, the new color value components are calculated according to the equation, which multiplies by the desaturation coefficient s each difference between the neutral component and the respective color value difference:

$$c_i' = neu + s(c_i - neu) \quad \text{for } 1 <= i <= N$$

where c_i' is the new color component value, modified by the desaturation function **78**. This modification of the color component values is preferably performed on the extended color gamut color values that have been encoded with the extended color gamut encoding function $H(x)$ **77**.

The desaturation coefficient s is determined from the color value in such a manner that the coefficient value is between 0.0 and 1.0. In addition, the value is lower for those color values that are most likely to produce color contouring or quantization. In other words, highlight color values having a relatively low saturation have a low desaturation coefficient s. The desaturation coefficient is computed considering the color value after the application of the inverse encoding function $G^{-1}(x)$ **56**, (recall the color component values range between 0 and 1.0). The desaturation coefficient is preferably found as follows:

$$s = 1 - \alpha + \alpha \frac{m_o}{m_{\max}} + \left[\alpha - \alpha \frac{m_o}{m_{\max}} \right] f(sat)$$

where α is an overall adjustment factor for the desaturation effect. A value of $\alpha = 0$ forces $s = 1.0$, so there is no effect on the saturation of any color value. The preferred value of α is 0.7, although good results can be obtained with values from 0.5 to 0.85.

m_o represents the slope of the modified inverse tone scale function $R_m^{-1}(x)$ **74** at a reference exposure. The slope of a function evaluated at a reference input can be determined by computing the ratio of the difference of the results

from evaluating the function at two input values (nearby and on either side on the reference input) to the difference of the two input values. As a default, the reference slope m_o of the modified inverse tone scale function at reference exposure of 0.855 is 1.32. The value of m_o does not vary based on the values of the color components of a particular color value.

m_{max} is the maximum of the slopes of the modified inverse tone scale function $R_m^{-1}(x)$ **74**, evaluated at each the value of each color component of the color value. However, only color component values greater than an initial threshold T_o are considered. Preferably, $T_o = 0.5$. The value of m_{max} is forced to be at least equal to the value of m_o.

f(sat) is a weighting function based on the saturation of the color value. The value of *sat* is the sum of the absolute values of the differences between the value of each color component and the neutral, as expressed by the equation:

$$sat = \sum_{i=1}^{P} |N - c_i|$$

when the color components of the color value are red, green and blue (indicated with *R, G*, and *B*, respectively),

$$sat = 1000(|N\text{-}R| + |N\text{-}G| + |N\text{-}B|)$$

where *N* is a color's neutral exposure value equal to $(R+B+G)/3$. (The 1000 is an arbitrary scale factor.)

The preferable function *f(sat)* is shown in FIG. 13. For inputs less than sat_o, the value of $f(sat) = 0$. Between sat_o and $2{*}sat_o$, the value of *f(sat)* linearly increases to 1.0. When the saturation *sat* of a color value is greater than $2{*}sat_o$, the value of $f(sat_o)$ is 1.0, in turn causing the saturation scale factor $s = 1.0$, resulting in no change in the value of the color components. The preferred value of sat_o is recommended to be 100.

In summary, the desaturation function **78** reduces the saturation of color values that are likely to produce color contouring or saturation artifacts. This is accomplished by determining a saturation coefficient *s* individually for each color value in an image, and using that saturation coefficient to reduce the saturation of the color value. Highlight color values with medium or low levels of

color saturation are subjected to a greater degree of desaturation in order to reduce the magnitude and frequency of objectionable color contouring and quantization artifacts. While the preferred method for determining the saturation coefficient has been described, those skilled in the art will recognize that many methods of finding the value of s can be used, without deviating from the spirit or scope of the invention.

The present invention describes a method by which a reconstructed extended gamut digital image can be formed from a limited color gamut digital image. The limited color gamut digital image is produced by applying a color adjustment function to an initial extended color gamut digital image. A reconstructed extended gamut digital image can be formed by applying an inverse color adjustment function to the limited color gamut digital image, but the resulting image is likely to contain color contouring and quantization artifacts. The present invention describes a method by which the inverse color adjustment function is modified to form a modified inverse color adjustment function which, when applied to a limited color gamut digital image, results in a reconstructed extended color gamut digital image having fewer artifacts. Due to the modification of the inverse color adjustment function, the reconstructed extended color gamut digital image generally has color values with less color saturation for highlight (nearly white) pixels than corresponding pixels from the initial extended color gamut digital image.

It will be obvious to one skilled in the art that the present invention can be practiced for limited color gamut digital images in many different limited color gamut color spaces. While the primary example discussed here has been with respect to the sRGB color space, there are many other color spaces that can be used in digital imaging applications. For example, other alternate video RGB color spaces and color spaces associated with other digital imaging devices such as digital cameras and printers are commonly encountered in many applications. Additionally, device-independent color spaces can also be used to represent limited color gamut digital images. While some of these color spaces can have larger color gamuts than others, they will all have a limited color gamut relative to

the original scene, particularly with respect to the luminance dynamic range, and therefore they can be considered to be limited color gamut digital images for the purposes of practicing the present invention.

The method of the present invention can be applied directly for digital imaging systems using any limited color gamut color space that can be encountered. Some digital imaging systems may need to deal with a plurality of different limited color gamut color spaces. There are several ways that the present invention can be extended to work within such systems. One method would be to simply apply the method of FIG. 1 to each of the different limited color gamut color spaces. However, this has the disadvantage that the reconstruct extended color gamut digital image step **65** would need to be reconfigured for each of the different limited color gamut color spaces.

Another approach to extend the method of the present invention to handle images in a variety of different limited color gamut color spaces is shown in FIG. 14. A fundamental feature of this approach is the introduction of the concept of a reference color space to which all of the different input digital images are transformed. This facilitates the usage of a common method for forming a reconstructed extended color gamut digital image. FIG. 14 shows two different input color spaces, although it will be obvious to one skilled in the art that it can be generalized to deal with any number of different input color spaces. In this case, an input digital image in a first input color space **100**, and a second input digital image in a second input color space **110** are shown, where the first and second input color spaces are limited color gamut color spaces such as the examples discussed above. A transform image from first input color space to reference color space step **105** is applied to the input digital image in the first input color space **100** to form a corresponding input digital image in reference color space **120**. Likewise, a transform image from second input color space to reference color space step **115** is applied to the input digital image in the second input color space **110** to form a corresponding input digital image in reference color space **120**.

There are many different color spaces that could be used as the reference color space. For example, a particular input color space can be designated to be the reference color space. Alternatively, some other color space can be designated as the reference color space. Ideally, the reference color space is selected to have a color gamut sufficient to represent input digital images in the set of different limited color gamut color spaces that the digital imaging application is expected to encounter without further limiting their color gamuts. An extended color gamut color space such as ROMM RGB is well-suited to this application. It should be noted that while ROMM RGB can be considered to be an extended color gamut color space relative to sRGB and many other limited color gamut color spaces, the input digital images in the reference color space **120** will still be limited to the gamut of the input color space. Additionally, the color gamut of a space like ROMM RGB will still be limited in comparison to the gamut of the original scene colors, particularly with respect to the luminance dynamic range.

Once the input digital image in the reference color space **120** has been determined, a procedure analogous to that shown in FIG. 1 can be used to determine a corresponding reconstructed extended color gamut digital image **135**. In particular, a reconstruct extended color gamut digital image step **125** is used to apply a modified inverse color adjustment function **130**, where the modified inverse color adjustment function **130** is formed as described above with reference to the preferred embodiment of this invention. The reconstructed extended color gamut digital image **135** is then well-adapted to be processed using one or more optional image enhancement algorithm(s) **140** to form an enhanced extended color gamut digital image **145**.

Depending on the particular set of limited color gamut color spaces, together with the characteristics of the input images and the image quality requirements of the digital imaging system, it may be possible to use a single modified inverse color adjustment function **130** independent of the input color space. The single modified inverse color adjustment function **130** could be optimized for one particular limited color gamut color space, or it might be a

compromise modified inverse color adjustment function that produced acceptable results for a set of different limited color gamut color spaces. The compromise modified inverse color adjustment function **130** could optimized in a weighted fashion, placing more importance on results for more popular limited color gamut color spaces. For example, nearly all consumer digital cameras are capable of producing images in the limited color gamut color space of sRGB. However, sYCC is currently less popular. The compromise modified inverse color adjustment function **130** could therefore be optimized by placing the most importance on sRGB, and lesser importance on sYCC. If a compromise modified inverse color adjustment function is used, it will often be desirable to design it so as to not substantially limit the color gamut of the limited color gamut digital images in the set of different limited color gamut color spaces. For example, it would generally not be desirable to limit the color gamut to that associated with any one particular limited color gamut color space.

In other cases, it will be desirable to use different modified inverse color adjustment functions **130** depending on the particular input color space. For example, if the first input color space is the sRGB limited color gamut color space, it may be desirable to use a modified inverse color adjustment function **130** specifically designed for limited color gamut digital images stored in that color space. But if the second input color space is the sYCC color space, it may be desirable to use a different modified inverse color adjustment function **130** optimized for that color space.

Rather than using one of a set of different modified inverse color adjustment functions **130** for each of the different limited color gamut color spaces, another alternative approach that can be used to achieve similar results is to make appropriate adjustments to transform image from the input color space to the reference color space steps (**105** and **115**). These adjustments would involve making modifications to certain colors in the limited color gamut digital image such that acceptable results can be obtained using a fixed modified inverse color adjustment function **130** independent of the particular limited color gamut color space in which the input image originated. For example, if it is known that the

fixed modified inverse color adjustment function **130** produces systematic errors in one region of color space when used with images originating in a certain limited color gamut color space, the corresponding color transformation could be adjusted to compensate for those errors. Likewise, if it is known that the fixed modified inverse color adjustment function **130** produces quantization or color contouring artifacts in one region of color space when used with images originating in a certain limited color gamut color space, the corresponding color transformation could be adjusted to reduce those artifacts.

Another approach that can be used to extend the method of the present invention to handle images in a variety of different limited color gamut color spaces is shown in FIG. 15. This figure shows two different input color spaces, although it will be obvious to one skilled in the art that it can be generalized to deal with any number of different input color spaces. As in FIG. 14, an input digital image in a first input color space **100**, and a second input image in a second input color space **110** are shown, where the first and second input color spaces are limited color gamut color spaces such as the examples discussed above. An input color space identifier **150** is used to identify the particular input color space associated with the input digital image. The input color space identifier **150** is preferably a piece of digital "metadata" that is stored together with the input digital image in the input color space. The digital metadata can be stored as part of the non-image header data in a digital image file, or can be stored in some form of digital memory associated with the digital image. In a preferred embodiment of the present invention, a list of possible input color spaces can be tabulated, and the color space identifier **150** is simply an index into the tabulated list. For example, color space #1 might be sRGB, color space #2 might be sYCC, etc.

The input color space identifier **150** is used as input to a color adjustment function selector **155**, which selects an appropriate modified inverse color adjustment function corresponding to the input color space from a set of modified inverse color adjustment functions **160**. Each of the modified inverse color adjustment functions in the set of modified inverse color adjustment

functions **160** is designed to produce the desired results for the corresponding input color space. A reconstruct extended color gamut digital image step **125** is used to apply the selected modified inverse color adjustment function to the input digital image in the input color space to form a reconstructed extended color gamut digital image **135**. As before, the reconstructed extended color gamut digital image **135** can then be processed using one or more optional image enhancement algorithm(s) **140** to form an enhanced extended color gamut digital image **145**.

The present invention is preferably practiced in an image processing system including a source of digital images, such as a scanner or digital camera, a computer programmed to process digital images, and an output device such as a thermal or inkjet printer. The method of the present invention may be sold as a computer program product including a computer readable storage medium bearing computer code for implementing the steps of the invention. Computer readable storage medium may include, for example, magnetic storage media such as a magnetic disc (e.g. a floppy disc) or magnetic tape; optical storage media such as optical disc or optical tape; bar code; solid state electronic storage devices such as random access memory (RAM) or read only memory (ROM); or any other physical device or medium employed to store a computer program.

The invention has been described in detail with particular reference to certain preferred embodiments thereof, but it will be understood that variations and modifications can be effected within the spirit and scope of the invention.

PARTS LIST

10	first or initial extended color gamut digital image
20	extended color gamut digital image
21	adjust color values to fit within limited color gamut step
22	color adjustment function
23	represent image in storage color space step
24	limited color gamut digital image
32	limited color gamut digital image
33	information describing color adjustment function
34	inverse color adjustment function
41	inverse encoding function $H^{1}(x)$
42	color primary matrix function E
44	tone scale function $R(x)$
46	encoding function $G(x)$
48	extended color gamut color value
50	limited color gamut color value
51	encoding function $H(x)$
52	inverse color primary matrix E^{-1}
54	inverse tone scale function $R^{-1}(x)$
56	inverse encoding function $G^{1}(x)$
62	modify inverse color adjustment function step
63	modified inverse color adjustment function
65	reconstruct extended color gamut digital image step
66	reconstructed extended color gamut digital image
72	decontouring matrix D
74	modified inverse tone scale function $R_m^{-1}(x)$
76	inverse decontouring matrix D^{-1}
78	desaturation function

PARTS LIST (con't)

81	solid line showing the inverse tone scale function **54**
82	dashed line showing a modified inverse tone scale function **74**
83	dotted line showing a modified inverse tone scale function **74**
100	input digital image in first input color space
105	transform image from first input color space to reference color space step
110	input digital image in second input color space
115	transform image from second input color space to reference color space step
120	input digital image in reference color space
125	reconstruct extended color gamut digital image step
130	modified inverse color adjustment function
135	reconstructed extended color gamut digital image
140	image enhancement algorithm(s)
145	enhanced extended color gamut digital image
150	input color space identifier
155	color adjustment function selector
160	set of modified inverse color adjustment functions